

DUNEFIELD ACTIVITY AND INTERACTIONS WITH CLIMATIC VARIABILITY IN THE SOUTHWEST KALAHARI DESERT

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ABSTRACT

An analysis is undertaken of the temporal variability of climatic parameters that influence dunefield aeolian activity. Data from seven meteorological stations in the southwestern Kalahari Desert are used, spanning the period 1960–1992. Erosivity is considered through analysis of wind data, and erodibility through analysis of precipitation and potential evapotranspiration, which together influence dune surface plant growth. The data are integrated using Lancaster's 'mobility' index which provides a measure of potential dune surface sand transport. This is renamed 'potential dune surface activity index', to reflect the actual characteristic that is measured. The subsequent analysis indicates that dunefield activity is episodic and temporally variable, that both erosivity and erodibility vary through time, and that present levels of activity cannot be characterized by a single simple state. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

The extent to which desert sand dunes or dunefields are affected by aeolian processes has been widely addressed through the consideration of broad climatic parameters (e.g. Ash and Wasson, 1983; Mabbutt, 1971; Muhs, 1985; Sarnthein, 1978). For example, precipitation rates have been used to delimit areas of active and 'fossil' dunes due to the positive relationship between rainfall and plant growth (Grove, 1958; Goudie *et al.*, 1973; Lancaster, 1981). Insufficient modern wind strengths (Ash and Wasson, 1983) and modern atmospheric circulation patterns incompatible with the orientation of dunes (Brookfield, 1970; Wells, 1983) have also been used to suggest that landforms are inactive or relict and inherited from past climatic regimes. More recently, however, the links between dunefield activity and simple regional climatic measures have been questioned and are now widely regarded as inadequately robust in view of the range of parameters that influence the operation of aeolian processes (Thomas and Shaw, 1991). These parameters, primarily rainfall, vegetation cover, wind regime and local topography, interact in a complex manner to influence sand transport at a variety of spatial and temporal scales (e.g. Ash and Wasson, 1983; Wasson and Nanninga, 1986; Wiggs *et al.*, 1994, 1995, 1996).

AIMS AND METHODS

The aim of this study is to provide an integrated analysis of temporal variations in wind strengths, precipitation rates and temperature in the southwest Kalahari dunefield. This is then used to consider the implications of the combined influence of these three variables on the potential for sand transport and dunefield activity. The data analysis is achieved through the use of an index which allows both the impact of climate on the wind

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environment and on the principal inhibitor of sand transport, surface vegetation cover (using precipitation and potential evapotranspiration as surrogate variables), to be inferred. Therefore both erosivity and erodibility are considered together.

Table I. Mobility equations

Reference	Equation	Threshold values	Region in which developed
Ash and Wasson (1983)	$M = [5 \times 10^{-4}(P)^2]/(AP/PE)$ $M = [3.8 \times 10^{-4}(U)^4]/(AP/PE)$	Mobility occurs when $M \geq 1.0$	Australia
Talbot (1984)	$C = V^3/(P)^2$	$C < 10$, dunes inactive $5 < C < 10$, limited aeolian activity $C > 10$, dunes active	Sahel
Wasson (1984)	$M = 0.21(0.13W + in PE/P)$	Mobility occurs when $M \geq 1.0$	Australia
Lancaster (1987)	$M = 0.25(0.10W + in PE/P)$	Mobility occurs when $M \geq 1.0$	Southwest Kalahari
Lancaster (1988)	$M = W(P/PE)$	> 200 , dune fully active (veg. cover $> 10\%$) $100-200$, dune plinths and interdunes vegetated (veg. cover = 12%) $50-100$, crestal areas only active (veg. cover $> 20\%$) < 50 , dunes inactive (veg. cover $> 20\%$)	Southwest Kalahari and Namib

Definitions: M = mobility, C = wind erosion factor, P = annual precipitation, $U = V - V_t$, V = mean annual wind speed, W = frequency of sand transporting winds, PE = annual potential evapotranspiration, AP = actual annual evapotranspiration

Five indices, some closely related, to assess desert sand dune mobility exist in the literature (Table I). These all operate on the principle that as sand transport potential increases, dune activity will increase and as moisture availability increases, dune activity will decrease. Lancaster's (1988) index was chosen for this study for a number of reasons. First, it is simple to calculate, which is an important consideration when the data are from basic meteorological sources. Second, it was developed by Lancaster using data from the southwest Kalahari. Third, Lancaster (1988) used field observations to suggest critical values of the mobility index (M) which differentiate degrees of activity ranging from fully active to completely inactive (Table I). Finally, the Lancaster (1988) index has been independently verified by Muhs and Maat (1993) in studies of dune activity in the United States.

Whilst noting that activity occurs along a continuum rather than in terms of distinct thresholds, Lancaster's (1988) division of the dune activity is in accord with the notion of a range of states of linear dune activity (Livingstone and Thomas, 1993). Linear dunes, however, are not necessarily 'mobile' landforms. The mode of development of these dunes means that sand is passed along the dune form resulting in an extension of the dune rather than a marked change in its physical position (Thomas, 1992). Vegetation can also play an important role in determining zones of sand movement across a linear dune profile (Wiggs *et al.*, 1996). Taking these points into consideration, it is appropriate that this index should be referred to as the 'potential dune surface sand activity' rather than 'dune mobility' index. In this paper the index is accordingly abbreviated to PA (potential activity).

Data from seven meteorological stations in and around the linear dunefield were obtained from the national meteorological services of Botswana, Namibia and South Africa (Figure 1). The data used in the study cover the period 1960 to 1992, but the completeness of data sets varies from location to location (Table II), with limitations in data (Bullard, 1994) primarily affecting information concerning the wind environment. The input of precipitation data to the index selected for this study was achieved by using daily rainfall data for the seven stations to calculate annual values. The temperature and rainfall data sets were complete for all stations, apart from an absence of any available rainfall data for Upington in 1968. Potential evapotranspiration (PE) values were generated using Thornwaite's (1948) method.

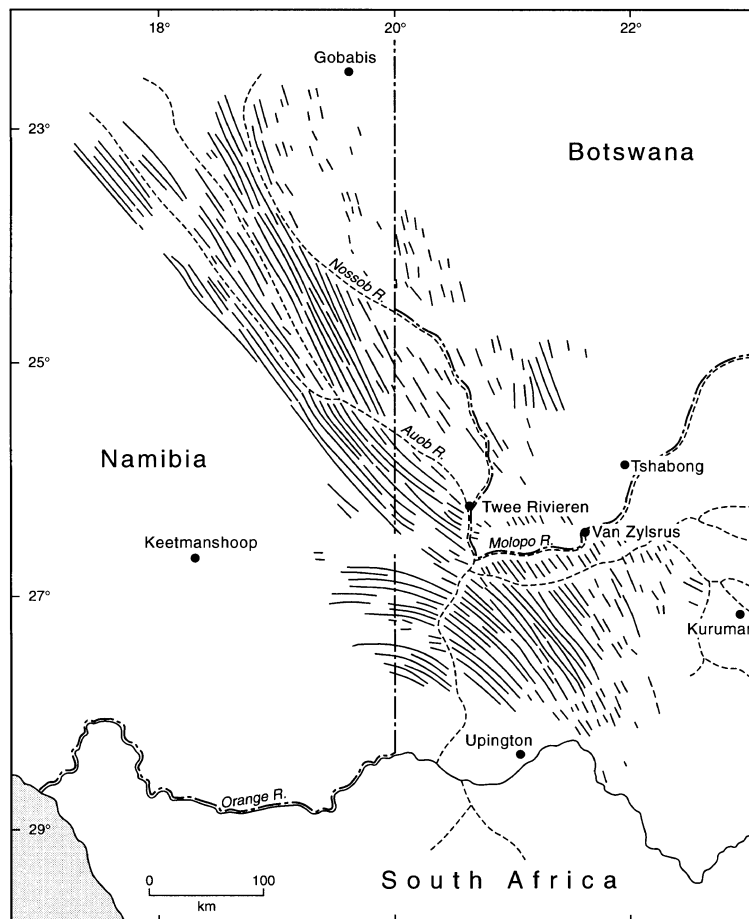


Figure 1. Map of the southwestern Kalahari linear dunefield showing locations referred to in the text

Table II. Available years of wind speed data used in this study

Gobabis	1966–83
Twee Rivieren	1961–92
Keetmanshoop	1971–81
Upington	1960–92
Tshabong	1980–90
Kuruman	1960–91
Van Zylsrus	1985–91

Annual values of M were calculated for each year and plots of annual M values for each station are shown in Figure 2; each graph shows the wind component of the index values on the vertical axis and the moisture balance component on the horizontal axis.

POTENTIAL DUNE SURFACE ACTIVITY IN THE KALAHARI DUNEFIELD

At Gobabis, in the north of the dunefield, and Van Zylsrus and Kuruman in the southeast, most years plot in the zone of the graph indicating no surface aeolian activity (Figure 2). The graphical plots permit the principal causes of inactivity to be deduced. At Gobabis, activity appears to be restricted by both low frequencies of sand-

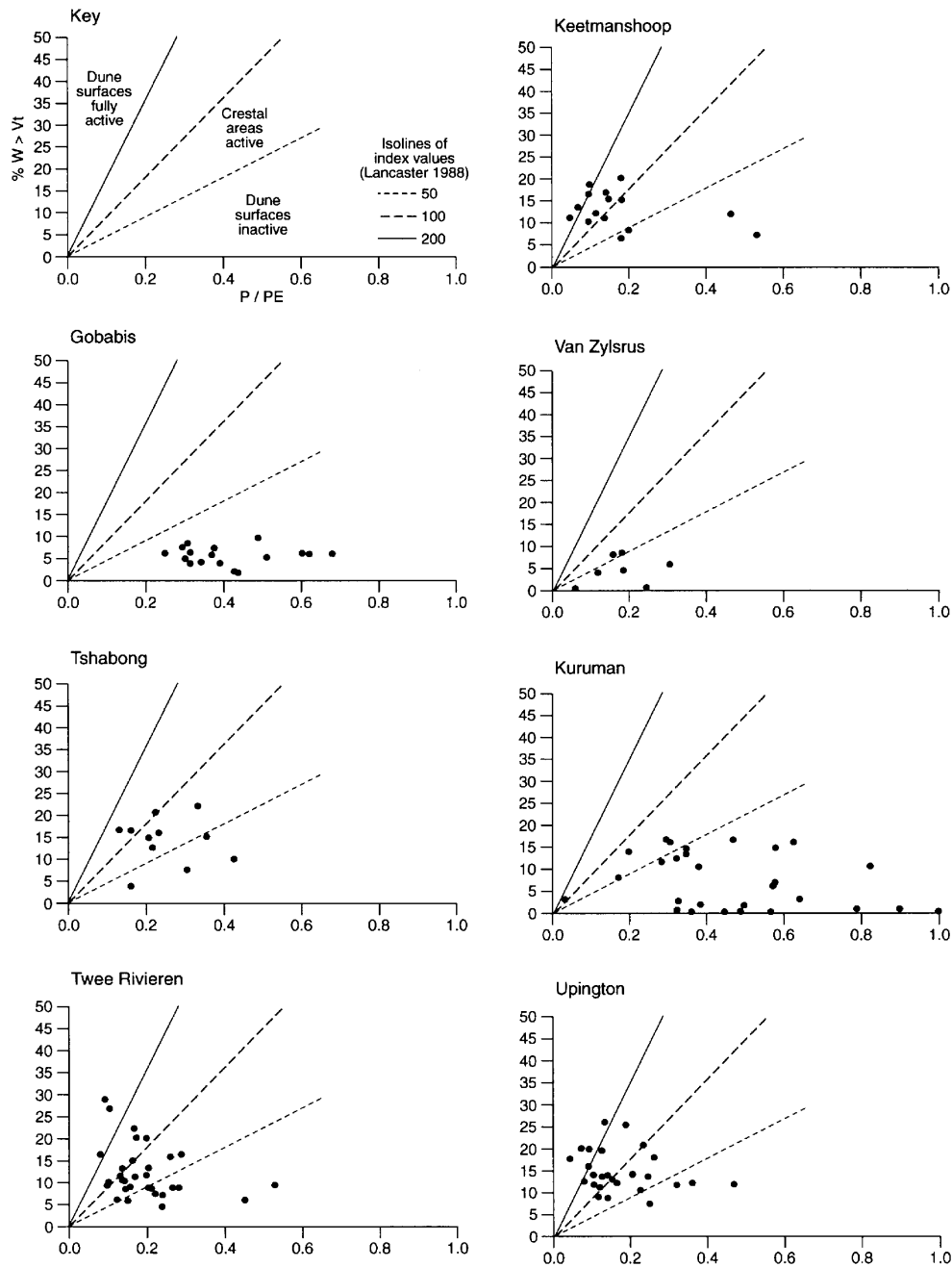


Figure 2. Potential dune surface activity index values (PA) for each location calculated using Lancaster's (1988) index (termed mobility index, M by Lancaster)

transporting winds and high levels of effective precipitation. At Van Zylsrus, effective precipitation values are low, restricting vegetation growth potential, but sand-moving winds are rare. At Kuruman, greater effective precipitation is the main limiting factor.

Crestal dune surface activity appears relatively important at Tshabong. At the remaining three locations – Keetmanshoop on the dunefield western margin, Twee Rivieren in the central dunefield and Upington in the

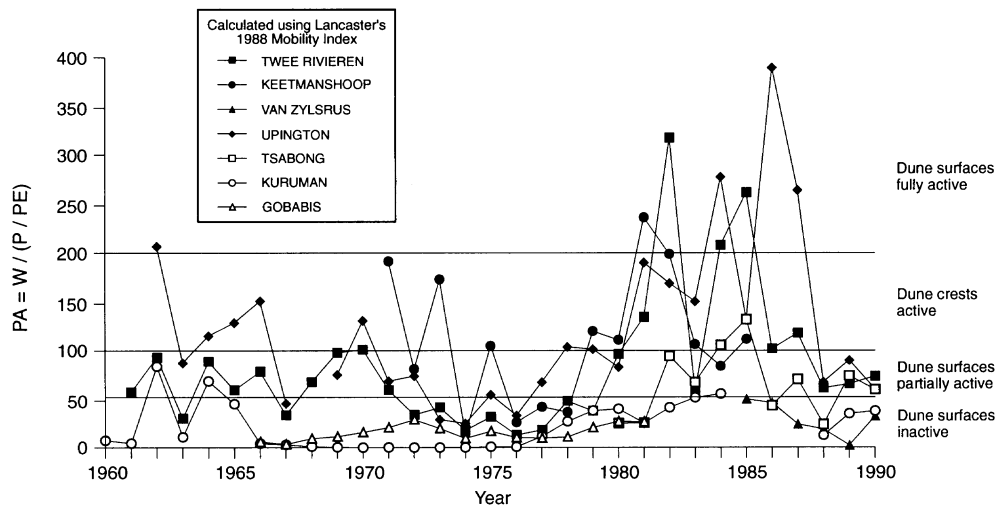


Figure 3. Temporal trends in PA values, 1960–1991. Thresholds of activity as determined by Lancaster (1988)

extreme south – partial surface activity dominates (Figure 2), but there is a broad spread of individual PA values across the four activity classes.

The range of values in the individual plots can be examined temporally in order to determine whether any trends in activity can be determined. The temporal trends in PA values for each station are shown in Figure 3. This suggests that in many parts of the dunefield, dunes experienced partial surface activity (principally in crestal areas) during much of the study period, with activity over greater parts of dune bodies primarily occurring during the 1980s.

A key aspect of the index is that it takes account of the effect of vegetation cover on sand movement, by assuming that the moisture component of the index represents an influence on plant growth. A limitation of this approach, especially when using the index to analyse a temporal sequence, is that by implication it assumes that plant cover in any one year is influenced only by the moisture regime of that year. In reality, vegetation cover does not respond instantly to excesses and deficits of rainfall, but reflects moisture availability over a number of preceding years (e.g. Wasson, 1976; Gibbens *et al.*, 1983). This is particularly important in a Kalahari context where the arid savanna grassland environment comprises both annual and perennial species (Thomas and Shaw, 1991).

In an attempt to incorporate a persistence effect, each annual value of the potential dune surface activity index was adjusted to take account of the previous 4 years by using a 5 year running mean to smooth the time series. Figure 4 shows the effect of this on the temporal pattern of index values. It should be noted that Van Zylsrus is omitted because once the total 7 year data run is adjusted to the 5 year running mean, only four values remain. An unsurprising effect of the smoothing procedure is that the representation of the extreme index values is reduced. Of note therefore (Figure 4) is that fewer years for any location fall in the complete dune surface activity area of the plot. This is in accord with field observations in the dunefield during the 1980s (e.g. Thomas, 1988), which indicated that even in the middle of the decade, dunes in the Uptington and Twee Rivieren areas were never totally devoid of vegetation (except where locally affected by grazing pressure) but did possess significant indicators of surface sediment movement in crestal and upper slope areas (Thomas, 1988).

VARIABILITY IN THE DUNEFIELD CLIMATIC ENVIRONMENT

Bullard *et al.* (1996) have established that during the period 1960–1991 the wind environment in the Kalahari dunefield displayed marked year-to-year variations in both resultant potential sand transport directions and the total drift potential (calculated after Fryberger, 1979). No clear spatial patterns of variation are apparent, but a notable temporal peak in potential sand transport occurred during the 1980s. Figure 5 shows the temporal variation in the percentage of sand-transporting winds used to calculate values of M in this study. This too

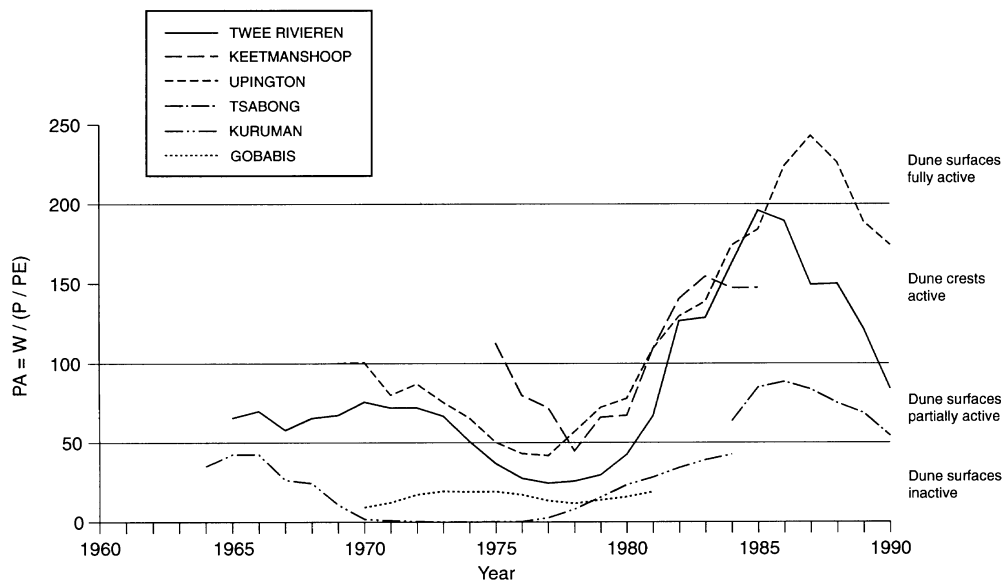


Figure 4. Values of PA modified using a 5 year running mean. Thresholds of activity as determined by Lancaster (1988)

shows a general increase in sand transport potential during the 1980s. While these temporal variations in windiness are incorporated within the index values of sand movement activity, so are variations in the other contributory climatic parameters of rainfall and, through its incorporation in the calculation of potential evapotranspiration, temperature.

Rainfall variations within the summer rainfall zone of southern Africa have been investigated in great detail by Tyson and co-workers (e.g. Tyson, 1986). Although this work has principally involved analysis of South African data, investigations of temporal patterns have also been reported for Botswana (see Thomas and Shaw, 1991). These studies strongly suggest an 18 year rainfall cycle for the region, linked to shifts in the Southern Oscillation (Tyson, 1986). Although falling within the region covered by such analyses, no detailed investigation of trends in the rainfall patterns in the dunefield area have been conducted. From a geomorphological perspective, such an investigation would complement information on changes in wind regime.

Rainfall data for the seven dunefield locations were therefore analysed for temporal trends. Figure 6 shows this information, with the raw annual data, compiled from monthly statistics, subjected to Tyson and Dyer's (1975) five-termed binomial low pass filter in order to reduce the influence of annual variations in the time series. It should be noted that in Figure 6 the longest period of available records has been used for each location, and in some cases, notably Van Zylsrus, this results in a longer period being considered than was possible with the wind data. The results show a noticeable year-to-year variation in rainfall, and distinctly wetter than average and drier than average periods can be recognized. Of note are the wet spell during the 1970s and the drought periods of the 1960s and 1980s. These three phases can be recognized throughout the dunefield.

Temporal trends in temperature data, which contributes to the PE component of the index, are shown in Figure 7 for the seven dunefield locations. Mean daily minima and maxima were averaged on a yearly basis to give the mean annual values. Absolute values and causes of temperature fluctuations are not of concern here. No evidence of a long-term trend is apparent and interannual fluctuations are relatively small, being no more than 20°C at any individual station. It can, however, be noted that at Keetmanshoop, Twee Rivieren, Upington and Gobabis, a notable dip in mean annual values occurred during the early 1970s.

IMPLICATIONS OF CLIMATIC VARIABILITY FOR DUNEFIELD ACTIVITY

All three climatic measures that contribute to the calculation of the potential dune surface activity index displayed marked variations during the study period. The period of the investigation is of insufficient length to

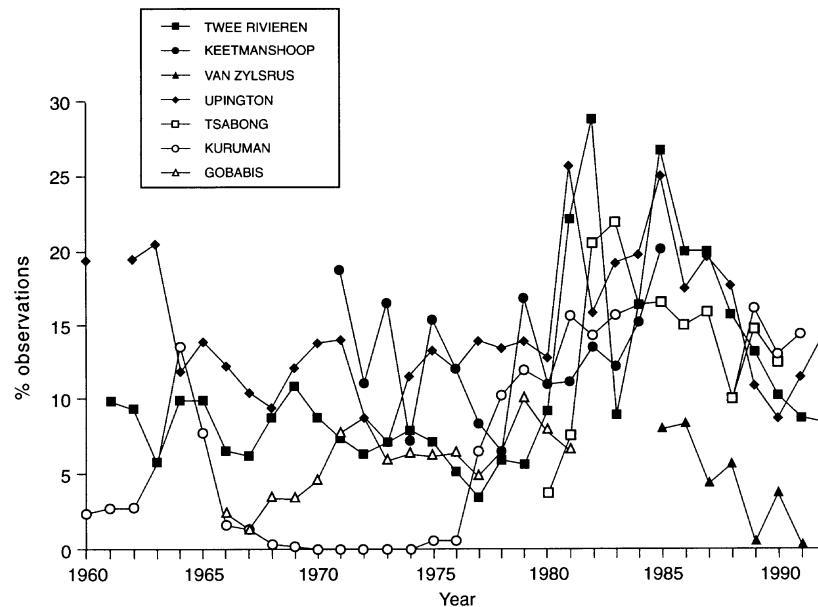


Figure 5. Temporal variations in the percentage of wind observations exceeding the threshold velocity for sand transport of Fryberger (1979) (5.97 ms^{-1})

suggest clear cyclicity in variations, but two key distinct periods can be identified. During the 1970s, index values show low aeolian sand activity throughout the dunefield, whereas activity levels were high in the 1980s. The 1970s was a period of higher than average rainfall in the dunefield. At the same time mean temperatures dropped, contributing to a reduction in potential evapotranspiration. These conditions would have favoured vegetation growth and low aeolian erodibility in the dunefield. Simultaneously, erosivity was often relatively low as the values in Figure 5 indicate. In combination, therefore, all the climatic parameters created conditions that were unfavourable for aeolian activity in the dunefield.

During the 1980s, drought conditions prevailed in the dunefield, with temperature levels also restored from their decline in the 1970s. Together, these favoured the reduction in the dunefield plant cover (Thomas, 1988). Therefore the erodibility of the dunefield was at its highest for the period under investigation. At the same time, erosivity, the percentage of sand-transporting winds, increased.

CONCLUDING REMARKS

This study of the interaction of the climatic factors that influence the operation of aeolian sediment transport processes in the southwestern Kalahari provides an indication of how aeolian activity can be investigated at the scale of a whole dunefield. The use of a potential surface activity index enables general trends in activity to be investigated in a manner that is not possible through detailed monitoring of processes which takes place at the scale of individual dunes (Wiggs *et al.*, 1996).

The index used in this investigation was first employed to consider the palaeoenvironmental development of the dunefield (Lancaster, 1988). Its application to the study of temporal trends in activity in the dunefield indicates how variable the index values are over a 30 year period. This dynamism in current dunefield climate and dune behaviour is important when overall dunefield status is considered. If mean values alone were used, they would mask both the period of dunefield inactivity during the 1970s and enhanced activity in the 1980s. This indication of episodicity in aeolian activity in the dunefield strengthens the earlier views of Thomas and Shaw (1990) and Livingstone and Thomas (1993), that dunefields cannot be considered in terms of single states of activity, and that issues of dunefield initiation and dunefield activity need to be handled distinctly when the palaeoenvironmental significance of partially vegetated dunefields is considered.

It has to be noted that the assumptions concerning levels of activity in the dunefield are based on the calibration of index values conducted by Lancaster (1988). This calibration can only be considered as a crude measure,

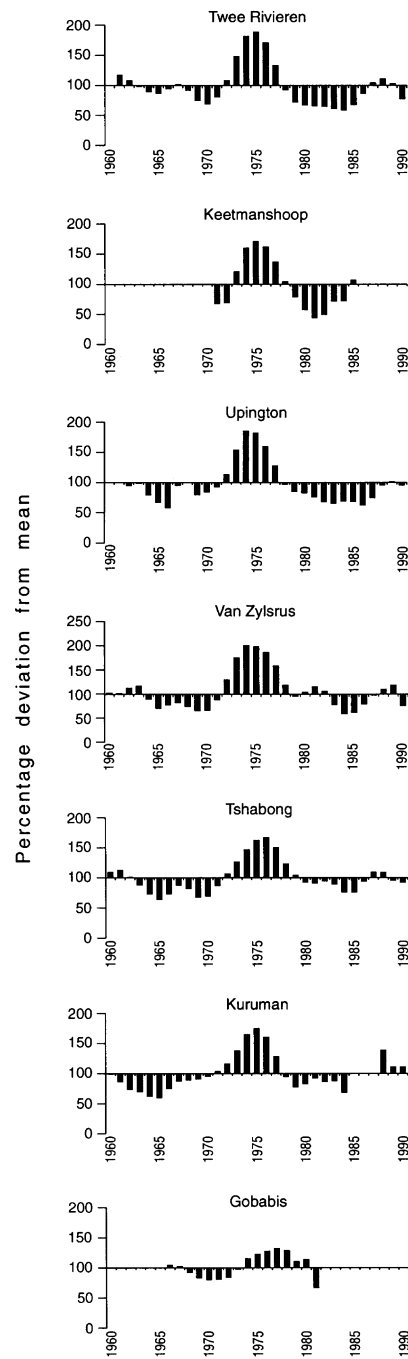


Figure 6. Temporal trends in dunefield rainfall for each location showing percentage deviation from the long-term mean

taking no account, for example, of the effect of the intrusion of dune bodies into the boundary layer on wind speeds and therefore erodibility. As such, the outcome of a study such as this can only be considered on a theoretical or broadly indicative level. Improved calibration may be possible through integration of the outcomes of detailed aeolian process studies into the interpretation of index values. Such an approach will, however, require the complementary collection of field monitoring data and general climatic parameters.

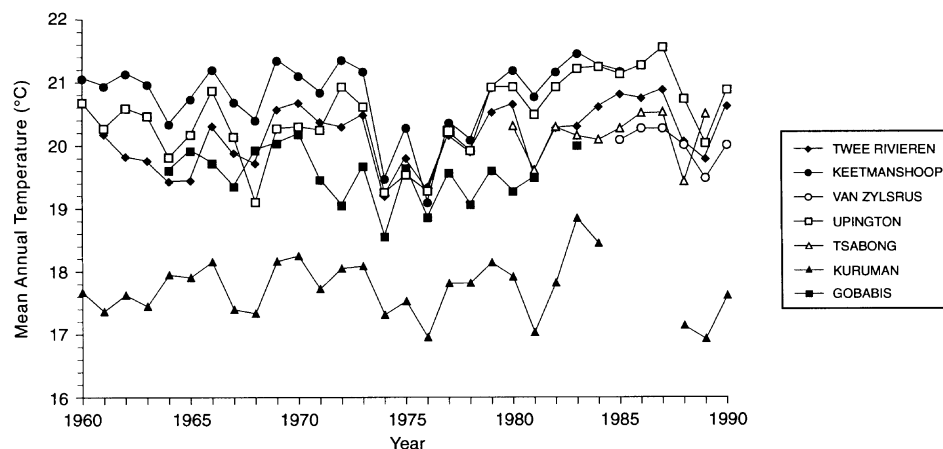


Figure 7. Temporal trends in mean annual temperature values

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